GRAIN YIELD AND YIELD STABILITY OF WINTER WHEAT CULTIVARS IN CONTRASTING WEATHER CONDITIONS

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ABSTRACT

Increasing yield without sacrificing yield stability is a major challenge for wheat breeding. This paper presents the yields and several stability parameters of modern Romanian winter wheat cultivars, tested in very diverse weather conditions in South Romania, and compares the information provided by various approaches. Fourteen Romanian winter wheat cultivars were tested along with the long term check Russian cultivar Bezostaya 1, in yield trials in 6 locations during 2002-2007, totaling 52 testing environments. The diversity of conditions included in the study is reflected by the large variation of average yields of the 15 cultivars in the 52 environments, which varied from only 291 kg/ha to more than 8000 kg/ha. Average yields were significantly correlated with water availability (rainfall + irrigation), suggesting that water stress was a major factor that influenced yield variation.

Average yield of each cultivar correlated significantly with all calculated stability parameters, except minimum yield, the coefficient of variation (*CV%*) and the regression intercept (*a*). Plotting phenotypic variances, or coefficients of variation, against average yields allowed identification of cultivars Izvor, Delabrad, Gruia, Faur and Glosa, showing smaller yield variation than expected based on their average yield. Ecovalence (W^2) did not describe yield stability, but characterized the similarity of response with the average of all tested cultivars. The regression analysis identified cultivars adapted only to favorable conditions with $b > 1$ and lower value of *a* (Dor and Alex) and cultivars adapted only to less favorable conditions with $b < 1$ and higher value of *a* (Bezostaya 1) Among the cultivars with wide adaptability, with *b* close to 1 and relatively large *a,* it was possible to identify those that better use good environments, with $b > 1$ (Glosa and Gruia), and those with better adaptation to lower yielding environments (in this case drier environments), like Izvor and Delabrad. Deviations from regression (δ^2) were almost perfectly correlated with the regression slope (*b*), suggesting that cultivars with higher regression coefficients had different response patterns to the environment than most tested cultivars.

Our study suggests that none of the used methods is sufficient for characterizing yield stability and for describing the specific response of each cultivar to the environmental variation. Plotting *CV* against average yield proved to be most useful in identifying cultivars with high and stable yield. Additional information was obtained by analyzing minimum yields as well as slopes and intercepts of cultivar regression lines on average yield of each trial.

Our results showed that high-yielding cultivars can differ in yield stability, and suggest that yield stability and high grain yield are not mutually exclusive.

Key words: Yield, stability, coefficient of variation, regression analysis, ecovalence, wheat.

INTRODUCTION

Increasing yield without sacrificing yield stability is a major challenge for wheat breeding, especially for regions characterized by large variation in weather and soil conditions. Several traits that are useful for better adaptation to unfavorable conditions can be counter productive, while other traits that can increase yielding potential can reduce adaptation to stress conditions. Calderini and Slafer (1999) found a general decrease in yield stability (assessed in absolute terms) with genetic gains in yield potential.

Breeding for yield stability has always been important, but will be increasingly so, as predicted climate changes will probably bring more weather variations from one year to another.

Many methods have been proposed for evaluating yield stability. Lin et al. (1986) presented 10 stability statistics and categorized them into four groups and three types of stability statistics:

- Group A, equivalent to Type 1, include standard deviation and coefficient of variation (Francis and Kannenberg, 1978), and are based on deviation from average genotype effect. A genotype is regarded as stable if its among-environment variance is small;
- Group B includes Type 2 statistics and are based on Genotype*Environment interaction. Ecovalence (Wricke, 1962), as well as the stability parameters proposed by Plaisted (1960) and Shukla (1972) are examples of Group B statistics. A genotype is regarded as stable if its contribution to the G*E interaction variance is small, i.e. its response to environ-

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ments is parallel to the mean response of all genotypes in the test;

- Group C also includes Type 2 statistics, but are regression coefficients based on regression of individual yields on an environmental index, which is usually the average yield of the trial. Regression coefficients proposed by Finlay and Wilkinson (1963), Perkins and Jinks (1968) or Eberhart and Russell (1966) are examples of Group C statistics;

- Group D includes Type 3 statistics and are based on deviations from regression. Examples are the deviation parameters of Eberhart and Russell (1966) or Perkins and Jinks (1968). A genotype is regarded as stable if the residual mean square from the regression model on the environmental index is small, i.e. the regression explains most of the variation.

Analyzing the numerous studies that compared various stability parameters and their relationship with yield, one can conclude that the results are much dependent on the diversity of environments and genotypes included in the study.

This paper presents the yields and several stability parameters of modern Romanian winter wheat cultivars, tested in very diverse weather conditions in South Romania, and compares the information provided by various approaches.

MATERIAL AND METHODS

Fourteen Romanian winter wheat cultivars (Fundulea 4, Flamura 85, Dropia, Rapid, Boema, Crina, Dor, Delabrad, Faur, Glosa, Gruia, Izvor, Alex and Romulus) were tested along with the long term check Russian cultivar Bezostaya 1, in yield trials in 6 locations from South Romania: Fundulea (irrigated and dryland), Mărculeşti (irrigated and dryland), Teleorman (irrigated and dryland),Valu lui Traian (irrigated and dryland), Caracal (irrigated and dryland), Şimnic (dryland) and Brăila (irrigated), during 2002-2007, totaling 52 testing environments. The 15 cultivars were included in a trial designed as a balanced 5x5 square lattice, with 6 replications.

The testing period included years with very diverse weather conditions, which can be characterized as follows:

- 2002: severe drought, heat;
- 2003: severe winter, drought, heat;
- 2004: normal weather conditions;
- 2005: excessive rainfall, lodging, sprouting;
- 2006: normal weather conditions;
- 2007: drought.

The diversity of conditions included in the study is reflected by the large variation of average yields of the 15 cultivars in the 52 environments, which varied from only 291 kg/ha to more than 8000 kg/ha (Table 1).

Table 1. Average grain yield of 15 winter wheat cultivars in 52 environments

Location	Year					
	2002	2003	2004	2005	2006	2007
Fundulea, irrigated	4627	3351	6330	4415	5033	5629
Fundulea, dryland	2167	1482	6687	4514	4607	3691
Mărculeşti, irrigated	4496	505	5286	4894	5300	-
Mărculeşti, dryland	2973	***291***	4991	4894	5255	3214
Teleorman, irrigated	5657	2788	-	5699	7724	-
Teleorman, dryland	3446	2505	6244	5962	-	5501
Valu lui Traian, irrigated	6391	-	7486	-	6126	4616
Valu lui Traian, dryland	3601	2116	-	-	6167	3796
Caracal, irrigated	**8049**	3254	4673	-	-	-
Caracal, dryland	5214	3231	4495	-	-	-
Şimnic, dryland	371	2278	-	5678	-	2839
Brăila, irrigated	-	-	6323	-	-	5822
Average yield/year	4272	***2180***	**5835**	5151	5745	4389

Yields in the 52 environments, averaged across cultivars were significantly correlated with water availability (rainfall + irrigation) from March 1st to June 30th (r = 0.46***) and from September 1st to June 30th (r = 0.35*). This suggests that water stress was a major factor that influenced yield variation.

Yields were analyzed by ANOVA and significance of yield differences was established by the Duncan test.

The following stability statistics were computed:

- phenotypic variance of cultivar *i* yields across environments:

$$s_i^2 = \sum (x_{ij} - \bar{x}_i)^2/(q-1)$$

- coefficient of variation:

$$CV_i = s_i / \bar{x}_i * 100$$

- wricke's ecovalence W^2:

$$W_i^2 = \sum (x_{ij} - \bar{x}_{i.} - \bar{x}_{.j} + \bar{x}_{..})^2$$

- regression coefficient (*b*) and the constant (*a*) of the regression line were computed using the "regression analysis" tool in Quattro Pro software:

$$b_i = \sum (x_{ij} - \bar{x}_{i.})(\bar{x}_{.j} - \bar{x}_{..}) / \sum (\bar{x}_{.j} - \bar{x}_{..})^2$$

- deviations from regression after Eberhart and Russell (1966):

$$\delta^2 = 1/(q-2)\left[\sum (x_{ij} - \bar{x}_{j.})^2 - b_i^2 \sum (\bar{x}_{.j} - \bar{x}_{..})^2\right]$$

Correlation analysis was used to study the relationship between yield and stability parameters, as well as between studied stability parameters.

RESULTS AND DISCUSSION

ANOVA showed that both environmental and genotype variances were significant when tested against the G*E mean square (Table 2).

Table 2. ANOVA for grain yield of 15 wheat cultivars in 52 environments

Source of Variation	df	MS	F
Environments	51	48.88	289.52
Cultivars	14	3.25	19.26
G*E interaction	714	0.17	
Total	779		

Grain yield of the studied cultivars averaged across the 52 environments varied from 3798 to 4819 kg/ha, with highest yields obtained in new cultivars and lowest yield in the historical check, the Russian cultivar Bezostaya 1 (Table 3). Older Romanian cultivars (Flamura 85, Dropia, Fundulea 4 and Rapid) were significantly inferior to new cultivars, but significantly superior to the historical check.

Table 3. Average, maximum and minimum grain yields and yield amplitude in 15 winter wheat cultivars

Cultivars	Average yield	Maximum yield	Minimum yield	Amplitude
Glosa	**4819**a	8912	228	*8684*
Gruia	4695ab	8549	*102*	8447
Dor	4645ab	8715	278	8437
Faur	4637ab	8328	161	8167
Alex	4622ab	8570	295	8275
Izvor	4601ab	8105	*459*	7646
Boema	4600ab	8252	286	7966
Delabrad	4547 b	8299	159	8140
Romulus	4502 bc	8003	331	7672
Crina	4496 bc	7865	200	7665
Flamura85	4337 c	7704	289	7415
Fundulea4	4312 c	8830	282	8548
Dropia	4287 c	7849	239	7610
Rapid	4240 c	7758	135	7623
Bezostaya 1	*3798* d	*7548*	197	**7351**

Yields followed by the same letter are not significantly different at P<0.05, according to the Duncan test.
Figures written in bold are the most desirable and those in italics are the least desirable.

Maximum yields varied from 7548 kg/ha in Bezostaya 1 to 8912 kg/ha in Glosa, while minimum yield varied from only 102 kg/ha in Gruia to 459 kg/ha in Izvor. Average yield was correlated with maximum yield but not with minimum yield (Table 5).

Yield amplitudes were very large, from 7351 to 8684 kg/ha and were correlated with average and maximum yield, but not with minimum yield.

Phenotypic variances across environments varied between 2055711 in Bezostaya 1 and 3878965 in Dor (Table 4). Correlation between average yield and variance was high and significant (Table 5), although some cultivars with very close average yield had different phenotypic variances.

Table 4. Several stability parameters in 15 winter wheat cultivars

Cultivars	Pheno-typic variance	CV%	W^2	b	a	δ^2
Glosa	3834967	40.6	7.20	1.07	44	*177.5*
Gruia	3587880	40.3	**3.84**	1.04	45	165.0
Dor	*3878965*	*42.4*	7.69	1.07	-153	170.7
Faur	3530076	40.5	6.49	1.02	63	161.7
Alex	3846436	42.4	4.86	*1.08*	-193	171.0
Izvor	3164093	38.7	9.59	0.96	319	140.0
Boema	3705458	41.8	6.50	1.05	-94	169.0
Delabrad	3260390	39.7	4.24	0.99	126	147.8
Romulus	3572820	42.0	5.70	1.03	-114	157.6
Crina	3639260	*42.4*	6.79	1.04	-149	166.2
Flamura 85	3177012	41.1	4.16	0.98	-28	141.0
Fundulea 4	3530912	43.6	11.29	1.01	*-201*	159.1
Dropia	3274548	42.2	8.90	0.98	-83	147.9
Rapid	3190657	42.1	7.26	0.97	-94	145.1
Bezostaya 1	**2055711**	**37.7**	*26.04*	**0.74**	**497**	**94.6**

Figures written in bold are the most desirable and those in italics are the least desirable.

Coefficient of variation (*CV%*) varied between 37.7% in Bezostaya 1 and 43.6% in Fundulea 4 (Table 4) and its correlation with average yield was low and not significant (Table 5).

Ecovalence (W^2) varied from 3.84 in Gruia and 26.04 in Bezostaya 1, and was negatively and significantly correlated with average yield.

Regression coefficients varied between 0.74 in the lowest yielding cultivar Bezostaya 1 and 1.08 in cultivar Alex. Correlation with average yield was high and significant. The intercept (a) also showed a large variation (from -201 in Fundulea 4 to +497 in Bezostaya 1), which was not correlated with average yield.

Deviations from regression varied from 94.6 in Bezostaya 1 to 177.5 in the highest yielding cultivar Glosa, the correlation with average yield being high and significant.

Table 5 also shows the correlation coefficients between the studied stability parameters. It is interesting to note that average yield correlated significantly with all stability parameters, except minimum yield, the coefficient of variation (*CV%*) and the regression intercept (*a*).

Maximum yield showed similar correlation, but was not significantly correlated with W^2, while minimum yield, was not correlated with any stability parameter.

Phenotypic variance was correlated with all stability parameters, except minimum yield. However, the coefficient of variation, which takes into consideration the normal relationship between the variance and the average, was not associated with average and maximum yield, yield amplitude or ecovalence (W^2), remaining correlated only with the regression coefficient (*b*), regression intercept (*a*) and the variance of deviations from regression (δ^2).

Table 5. Correlations between average yield and several stability parameters

Parameters	Average yield	Maximum yield	Minimum yield	Ampli-tude	Phenotypic variance	CV	W^2	b	a
Average yield	1								
Maximum yield	*0.70*	1							
Minimum yield	0.12	0.03	1						
Amplitude	*0.66*	*0.98*	-0.17	1					
Phenotypic variance	*0.86*	*0.69*	0.10	*0.66*	1				
CV	0.21	0.30	0.03	0.29	*0.68*	1			
W^2	*-0.77*	-0.34	0.03	-0.34	*-0.81*	-0.47	1		
b	*0.87*	*0.65*	0.08	*0.63*	*0.99*	*0.66*	*-0.86*	1	
a	-0.36	-0.35	0.01	-0.34	*-0.78*	*-0.97*	*0.63*	*-0.78*	1
δ^2	*0.87*	*0.72*	0.01	*0.70*	*0.99*	*0.64*	*-0.77*	*0.98*	*-0.75*

Coefficients written in *italics* are significant at P<0.05

Despite existence of several highly significant correlations, it is obvious that each stability parameter, and especially those belonging to different groups according to Lin et al. (1986), describe different aspects of G*E interaction.

Phenotypic variance (s_i^2) is the classical measure of variation, but has the disadvantage of being dependent on the yield level. However, if we exclude the historical check Bezostaya 1, the lowest yielding cultivar, which showed the lowest overall yield variation, several exceptions from the expected correlation between average and variance can be found.

Cultivar Izvor had the second lowest phenotypic variance, but was in the same significance group with the highest yielding cultivar (Glosa) and with the cultivar Dor, which had the highest variance. The lower yield variation at a higher average yield level in cultivar Izvor, can be explained by its superior drought resistance, related to a higher level of osmotic adjustment (Bănică et al., 2008).

Plotting phenotypic variances against average yields allows identification of cultivars deviating from the general relationship (Figure 1). Cultivars Izvor, Delabrad, Gruia, Faur and Glosa showed smaller yield variation than expected based on their average yield.

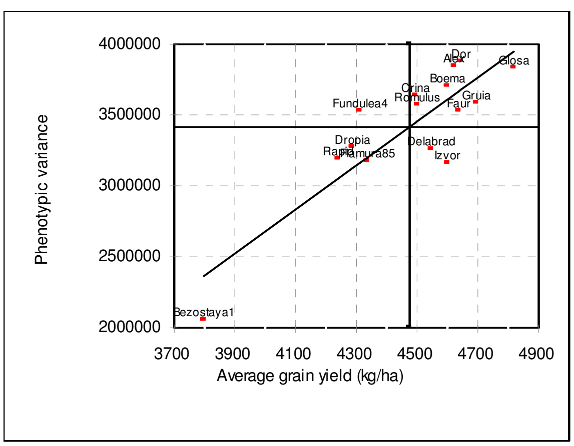

Figure 1. Grain yield averaged over 52 environments and variances in 15 wheat cultivars

The coefficient of variation (CV_i) is often used to reduce the effect of averages on direct measures of variation (variance or standard deviation).

The degree of this reduction can vary, from insufficient to exaggerated, depending on the size variation of averages and standard deviations respectively. Jalaluddin and Harrison (1993) found that the coefficient of variation (CV_i) was not a reliable statistic to describe genotypic stability because its rank order was induced by the rank order of average yields. In our study coefficients of variation were not significantly correlated with average yields, or with maximum yields or yield amplitudes.

Ortiz et al. (2001) suggested that it may be possible to select simultaneously for high and stable grain yield by selecting out yielders that exhibit a low CV. Figure 2 shows that cultivars Izvor, Delabrad, Gruia, Faur and Glosa had higher yields and lower CV than the average of all studied cultivars.

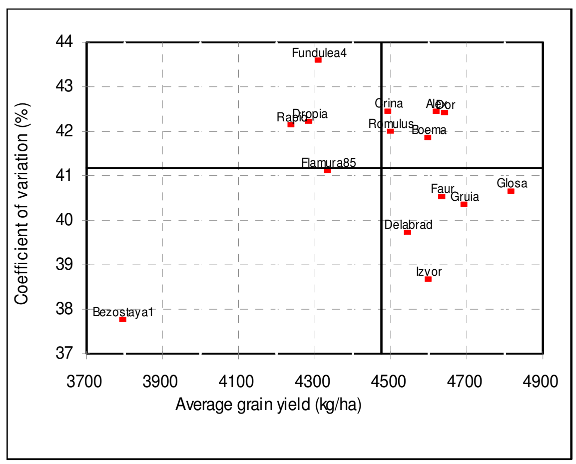

Figure 2. Grain yield averaged over 52 environments and coefficient of variation in 15 winter wheat cultivars

Minimum yield is seldom considered a stability parameter. However, for farmers working in unfavorable environments, it can be very important. Plotting the minimum yield against the average yield can help indentify cultivars which have good average performance, but also ensure a better yield in the worse conditions (Figure 3). Cultivars Izvor, and also Alex, Boema and Dor had higher both average yield and minimum yield better than the average of all tested cultivars.

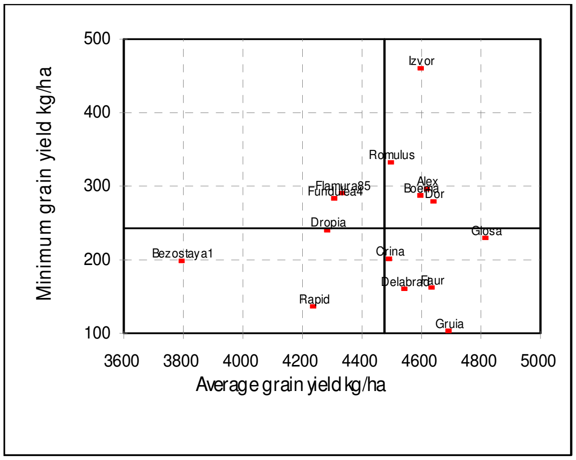

Figure 3. Grain yield averaged over 52 environments and minimum yield in 15 winter wheat cultivars

Ecovalence (W^2), i.e. the contribution of each cultivar to the G*E interaction variance, gives a completely different classification of cultivars. Bezostaya 1, which had the lowest yield variation, had the highest ecovalence, followed by Fundulea 4, a cultivar with high *CV* and Izvor, a cultivar with low yield variation. Clearly, ecovalence did not describe yield stability, but only showed the similarity of response with the average of all tested cultivars. Bezostaya 1, which did not respond to favorable environments, Fundulea 4, which gave high yields in good environments but was more affected by drought, and Izvor, which performed better than most cultivars in unfavorable conditions, all were classified by ecovalence as „unstable", because of their specific response to environmental conditions was different from the average response of all tested cultivars. These results demonstrate that ecovalence is not useful for estimating yield stability.

Regression analysis has been widely used in analyzing G*E interaction and yield stability. According to Keim and Kronstad (1979) a genotype is regarded as adapted to unfavorable environments when the regression coefficient $b < 1$ and a (the regression constant) is large, adapted to favorable conditions when $b > 1$, and widely adapted to diverse environments when $b \geq 1$ and a has a high value.

This approach has been criticized because linear regression on average yield of the trial often explained only a small part of yield variation (Baker, 1969: Byth et al., 1976). In our study, regression on yield averaged across cultivars explained a large part, from 0.86% to 0.98%, of yield variation in individual cultivars, so this criticism does not apply in our case. Indeed, when applied to our data the regression analysis identifies cultivars adapted only to favorable conditions with $b > 1$ and low value of a (Dor and Alex) and cultivars adapted only to less favorable conditions with $b < 1$ and high value of a (Bezostaya 1). Among the cultivars with wide adaptability, with b close to 1 and relatively high values of a, one can identify those that better use good environments, with $b > 1$ (Glosa and Gruia), and those with better adaptation to lower yielding environments (in this case drier environments), like Izvor and Delabrad.

However, the other disadvantages of the regression analysis remain. Nurminiemi and Rognli (1996) demonstrated that regression analysis of yield stability is strongly affected by companion test varieties and locations. As a consequence, inferences based on one set of trials might not prove true if a cultivar is tested along with other cultivars.

Deviations from regression (δ^2) were almost perfectly correlated with the regression slope (b), i.e. regression lines with higher slopes had larger deviations of individual yields. As Westcott (1986) noticed, a variety could have marked deviations from linear regression, not because it was inherently irregular, but because it showed a different response pattern from the majority of the group with which it was being compared. Our results suggest that the cultivars with higher regression coefficients had different response patterns to the environment than most tested cultivars.

When selecting the best method for characterizing yield stability in a breeding program, an important criterion is heritability. According to Jalaluddin and Harrison (1993) only b and *CV* were repeatable across subsets of environments. According to Ortiz et al. (2001) *CV* had the highest narrow-sense heritability ($h^2 = 0.522$). Lin and Binns (1991) also concluded that stability parameters of types I (variance of a genotype across environments) and 4 (years within locations MS for a genotype, averaged over all locations) are heritable, and thus useful for selection, while those of types 2 (genotype x environment (GE) interaction effect for a genotype, squared and summed across all environments) and 3 (the residual mean square (MS) of deviations from the regression of a genotype on an environmental index) are non heritable, and thus not useful.

From this point of view, and also based on our results showing that *CV* is relatively more independent of average yield level, we consider that plotting *CV* against average yield can be most useful in identifying cultivars with high and stable yield.

Other widely used stability parameters are less indicative of yield stability, but can provide additional information about the cultivar response to environmental conditions. Minimum yields should not be neglected in selecting cultivars able to provide best protection to farmers against worse climatic conditions. Regression analysis on an environmental index can be useful if regressions explain a large part of total yield variation. In this case, both the regression line slope and intercept can help characterize the specific cultivar response.

CONCLUSIONS

The results of our study suggest that none of the used methods is sufficient for characterizing yield stability and for describing the specific response of each cultivar to the environmental variation.

Plotting *CV* against average yield proved to be most useful in identifying cultivars with high and stable yield. Additional information was obtained by looking at minimum yields, which identified cultivars with better performance under worse conditions.

In our data set regressions of individual cultivars yields on average yield of each trial explained a large part of total yield variation. In this case, both the regression line slope and intercept helped characterize specific cultivar responses.

Our results showed that high-yielding cultivars can differ in yield stability, and suggest that yield stability and high grain yield are not mutually exclusive.

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